AGU Advances

Authors' Response to Peer Review Comments on

The key role of production efficiency changes in livestock methane emission mitigation

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Authors' Response to Peer Review Comments on Original Version of Manuscript (2021AV000391)

Dear Editor and Referees,

We would like to thank the editor and the two referees for their valuable comments on the content of our manuscript and for their suggestions for improving the document. Following the suggestions and comments, we have carefully revised our manuscript (referred to as MS hereafter). We believe that the revised version satisfactorily addresses the referees' questions and concerns, and that the manuscript has improved as a result. In this reply, we seek to clarify the issues raised by the referees, point by point. Please find our detailed responses (in blue) to the referees' comments (in black). For your convenience, all the changes in the revised MS are in red, and the corresponding line numbers are noted in the point-by-point responses.
Thank you again for your time and effort on our manuscript.

Yours sincerely,
Jinfeng Chang on behalf of all co-authors

Reviewers' Comments:

Reviewer #1 (Formal Review for Authors (shown to authors)):

Review for AGU Advances, "The key role of production efficiency changes in livestock methane emission mitigation"
The authors look at historical and projected changes in global estimates of livestock methane emissions as well as in emissions intensity (methane emitted per amount of protein produced), and do a sensitivity analysis of the impacts of changes in livestock numbers and emissions intensity on future emissions. Their main conclusions, based on these projections, are: both decreased demand for livestock products and continued increases in production efficiency/decreases in emissions intensity will be needed to mitigate the climate effects of livestock methane; and that decreasing emissions intensity across large parts of the globe will have a much greater mitigating effect than moving between the demand-side scenarios of 'business as usual', 'stratified societies', and 'towards sustainability' (at least, that is the message I got from Fig. 4). This is an important message for guiding future research, climate action, and political/agricultural planning; I'd like to see it explained more thoroughly in the key points and abstract. The authors rely on the new IPCC revisions to the guidelines, the Gridded Livestock of the World distribution, and on FAO data, making this a paper of significant interest but not 'groundbreaking'. The contributions/novelty of the study are in the analysis/sensitivity analysis of emissions intensity and the future projections.
[Response] Thanks for the correct summary of our study. We thoroughly revised the key points, abstract and plain language summary (L22-52) to emphasize the advancement and major implications of our study.

I have only a few minor concerns:
1. Their uncertainty on emissions seems quite low (e.g. lines 339-341, they have 121 Tg CH4 / year ± 4 Tg, for example compared to my estimate of 118 ± 18 Tg). The authors refer the reader to the methods section for description of treatment of uncertainty but I didn't find any useful description in 2 readings (please pardon me if I missed something.). In my 2017 manuscript, which the authors have compared to, I mention:
Uncertainty on IPCC livestock CH4 emissions factors is given as {plus minus}30% [4], and is defined as representing {plus minus}1.96 times the standard deviation of the mean [34]. In order to be combined mathematically [34,35] with our estimates of uncertainty on other C fluxes, we used 15.3% (30% divided by 1.96) as the uncertainty for all calculated CH4 quantities.

Is it possible that the authors treated that 30% "uncertainty" given in the IPCC guidelines as variance, which would result in much lower standard deviation? Even using Monte Carlo simulations as mentioned in the methods, the input uncertainty on the actual emissions per animal should result in higher uncertainty than theirs, which is about 3.3% of the mean estimate. I have not read the 2019 IPCC revisions (and hope that I won't have to!), so it is possible that there is now a lower uncertainty given on methane estimates, or that the authors did some work to narrow those uncertainties. That would be a significant development, because of the challenges associated with measuring CH4 from livestock and manure across many individuals and situations... I would like to see this discussed more clearly, and if the 30% error is still current, then their uncertainty bands should either be

widened or provide a description of how they are so narrow. I do admit that I'm not an expert in either statistics or uncertainty analysis, so feel free to clarify if I am in error.
[Response] In this study, uncertainties were derived from Monte Carlo ensembles (n = 1000) from the range of uncertainties reported for the parameters and / or emission factors used in the calculations (ranging from 13.4% to 20%; see revised section 2.3). In the previous version, we assumed independent uncertainty for each country and each livestock category for the Monte Carlo ensembles. However, we realized that the uncertainties of parameters and emission factors given by the IPCC guidelines are derived from various studies across the world and expert judgement, thus should not be independent for each country. Therefore, in the revised MS, we applied the uncertainties not independent for each country and but still independent for each livestock categories in the Monte Carlo ensembles. We also assumed independent uncertainties for CH_4 emissions from enteric fermentation and from manure management. As a result, the uncertainties (presented as standard deviation) for global enteric fermentation, manure management and total CH_4 emissions by 2010 are 11.8%, 8.2%, and 10.5%, respectively using the 2019 MT method, and 12.4%, 7.7%, and 11.1%, respectively using the 2019 T1 method. We added a new section "2.3 Uncertainty estimates" (L285-204) in the revised MS.

2. The authors base their future projections on the ideas that i) countries that have not decreased their livestock emissions intensity over the past two decades will also not decrease them in the future, and ii) countries that have decreased their emissions intensity will continue to. In some ways this is likely-e.g. arid, poor countries will continue to have extensive livestock production with poor feed quality, low productivity, and high emissions just by nature. However, I don't know if countries that already have high production and low emissions intensities can continue to improve, especially under the constraints of commercial, industrial agriculture (e.g. supplements may reduce enteric fermentation, but they will increase the cost of producing meat too much, and so will not be used broadly). Increasing demands for food and biofuel crops, along with more frequent climate extremes, decreasing availability of groundwater, rock P, and etc., may even decrease the quality of feed and increase emissions in some of these wealthy developed countries. These issues are addressed in the last paragraph of the manuscript somewhat. Still, I think that the opposite of these two scenarios might almost be more feasible (i.e. keep productive/efficient countries close to where they are now, and put resources towards improving feed quality and efficiency in the countries that have not improved yet). A formal analysis of that possibility is not necessary, but I would like more discussion of how the authors envision these two scenarios occurring in the real world. Livestock breeding and management have already resulted in systems that are fragile, not resilient, and do not adequately handle their manure or emissions. But demand in wealthier countries is now putting a premium on 'free range' chicken and grass-fed beef; these move livestock operations away from the very high efficiency that is needed for the projections made in the paper....
[Response] In fact, our results showed that small or no improvement was projected for many developed countries by the "*improving efficiency*" pathway (see Figure S10), as the already high efficiency (Figure S10) and the minimum emission intensity per kg protein for each livestock category *k* ($EF_{protein,k,min}$) as a threshold set in the scenario (L342-346). On the other hand, developing countries such as Tanzania, Niger, Madagascar, and Sudan

have large potential to mitigate their CH_4 emission through decreasing emission intensity. We added some discussions on this issue (L622-633) as "Livestock productivity of milk and beef in most developed countries is already high nowadays (methane emission intensity is already low; Fig. 2), and there is only little room for methane reduction through productivity increase (Figure S10). On the other hand, further productivity increase requires high shares of concentrates (i.e., potential competition with human nutrition from plant-based food (Gill et al., 2010)) and encounters potential health problems in cows (see review by (Herzog et al., 2018)). In addition, the intensive livestock breeding and management have resulted in fragile systems that do not adequately handle their manure causing air and water pollution. There is a trend that some developing countries are moving from high efficiency systems towards more extensive livestock systems (such as "free range" chicken and grass-fed beef; e.g., (Cheung & McMahon, 2017)). Therefore, there is possibility that the emission intensity per kg protein in those developed countries will increase, opposite to our assumption of constant of decreasing emission intensity.". Further discussion on the potential strategies and their adaptability issues and side-effects were revised following suggestions of reviewer #2 (L641-665).

Minor issues:
Line 67, unclear whether livestock CH4 = fossil fuel CH4 or = fossil fuel CO2 equivalent or something else?
[Response] For clarity, we revised the sentence (L60-61) as "Currently, livestock production represents a third of the global anthropogenic methane emissions, comparable to the magnitude of fossil fuels methane emissions (Saunois et al., 2020).".

Several times the word "marginal" is used to describe slight decreases or other (e.g. line 457); but this word has very specific statistical, ecological, or economic usages, and is not clear what is meant in these instances.
[Response] Thanks for point this out. We replaced the word "marginal" to "slight" in line 503 and 526 of the revised MS.

Also line 457, use of the IPCC category "other cattle" for all cattle not used for dairy, can be confusing to people who don't use IPCC guidelines on a regular basis. Might be worth defining, putting in quotes, or changing to something like "meat and other non-dairy cattle" for clarity.
[Response] Thanks for the suggestion. For consistency, we used "dairy cows" and "meat and other non-dairy cattle" across the revised MS.

Lines 384-5 and Fig 1B-decreasing emissions intensity has an opposite effect from increases in population. The way the authors are trying to show and attribute the changes to these opposite effects was quite confusing to me.
[Response] In Fig. 1b, the intensity indicates emission intensity per head of livestock rather than per protein production. The emission intensity per head is increasing during the past two decades as the mean body size, meat and milk production per head is increasing. We clarified this in the revise MS (L424-427) as "We estimated that 73% of the increase in global emissions between the two periods is explained by increasing livestock numbers,

the remaining 27% due to increasing emission intensities per head in most regions (i.e., larger mean body size, meat and milk production per head)."

Lines 412-13. Sheep and goats have higher emissions intensity than beef, presumably due to their poorer/less digestible diets. However, in a broader view, they may also have quicker lifecycle, less carcass waste per unit protein, and/or less dependence on fertilizer/crop emissions and land use change emissions, and etc. These issues can get quite broad, but I hate to see industrial beef get unduly promoted at the expense of animals that can be of such great importance in subsistence diets.
[Response] We fully agree your point of view. In the revised text, we added the following discussion (L459-462) "Higher methane emission intensities of goats and sheep meat than that of beef are mainly due to the low digestibility of feed (low-quality roughage). On the other hand, it means that goats and sheep depend less on human-edible feed and avoid food-feed competition (Mottet et al., 2017; Van Zanten et al., 2018)."

Lines 468-479 I had a hard time following the meaning of this paragraph, can it be rephrased for clarity?
[Response] For improving the clarity, we revised the paragraph (L514-523) as:
"It is noteworthy that the intensity change estimates using the 2019 MT method usually show smaller decreases or even increases in emission intensities per protein production than the estimates using the other two methods (Fig. 3). The estimates using the 2006 or 2019 T1 methods consider the fixed emissions per head of livestock, and underestimate the increasing trend of total emissions caused by the increasing yield and liveweight (Fig. 1b). Thus, with an increasing trend of protein production per head of livestock in reality, using the 2006 or 2019 T1 methods partly overestimates the decreasing trend from emission intensities per protein production. Our results highlight the key role of accounting for methane emissions due to productivity and liveweight changes (as in the 2019 MT method) in capturing the temporal changes in the emission intensities per protein production."

Fig. 5 was difficult for me to see, even enlarging the pdf version by a lot. This might not be easy to remedy, but it was hard to find the black dot among all the other lines, and dots. Might it be easier to see with less than the top ten countries shown?
[Response] To improve the clarity, we showed only the figure on all livestock in the main text (see revised Fig. 5), and put other sub-plots to the Supplementary Information (Figure S15-17). We also enlarged the figures from four to three subplots per line, enlarged the dots, and added a color bar to indicate the mitigation potential from large to small.

Overall, I think this is a fine manuscript. Please note that like everybody else these days, I have too much to do and not enough time to do it, and haven't slept enough. If I missed or misinterpreted something, please just point it out.
[Response] Thank you very much for the valuable comments and suggestions.

Reviewer #3 (Formal Review for Authors (shown to authors)):

The authors investigate how these systematic uncertainties in estimating methane emissions from livestock may affect future projections of livestock GHG emissions. The

show the effect of contrasting methodologies for estimating emission on the resulting magnitude of emissions. The authors also work on options to reduce emissions through reduced consumption and improved production efficiency.
The paper fits well to the AGU Advances aims.
Detailed comments:
L 91 : correct reference (without author initials) (P. J. Gerber et al., 2013)
[Response] We corrected it across the MS.

L 144 "For emissions from enteric fermentation, we used the IPCC Tier 1 method (IPCC, 2019 Vol. 4, Chapter 10, Eqn 10.19)": one of the major refinements was the introduction of Tier 1a emission factors for enteric fermentation to account for increases in production levels in cattle raised in countries that apply a Tier 1 methodology for estimating enteric CH4 emissions. How did you account for this update in CH4 emission factors?
[Response] In the revised MS, we presented the estimates of enteric fermentation CH_4 emissions using the IPCC Tier1a method for a comparison. We 1) added the description of the Tier 1a method in section 2.2 (L173-184); 2) compared the global estimates with that from the Tier 1 method in section 3 (L379-388); and 3) added the global values in Table S2. We also revised the R code to make estimates using the Tier 1a method.
L173-184: "For dairy cows, meat and other non-dairy cattle and swine in Latin America, Africa, Middle East, Asia and India sub-continents, regional CH_4 Tier 1a emission factors from Table 10.10 and Table 10.11 of (IPCC, 2019) Vol. 4, Chapter 10 and the regional shares between high ($S_{high,r}$) and low productivity systems ($S_{low,r}$) calculated by Eqn (1) were used. Due to the limited regional information on the production systems and on their time variation from the IPCC guideline, emissions from other livestock categories are the same as those of the 2019 T1 method, and the shares between high and low productivity systems are time-invariant in our estimate."
We found that global estimates using the 2019 T1a method (see section 2.2) are nearly the same as that using the 2019 T1 method (< 0.2% differences; Table S2) with differences ranging from 0.01% to 3.4% in regional estimates, thus we do not discuss the emissions using the 2019 T1a method in the rest of the MS.

L 140: Estimating livestock CH4 emissions using IPCC Tier 1 methods from the 2019 Refinement (the 2019 T1 method: While I understand the procedure that you choose to estimate the emission factors, I would like to have some information integrated into the text that this is a purely academic exercise to show the effect of the Tiers on total emissions. All countries where cattle are key sources (and this applied to countries with high productivity systems) have to use a Tier 2 approach to estimate their emissions. This is so, because it is well acknowledged that applying a Tier 1 approach for high productivity systems will entail large uncertainties in the emission estimates.
[Response] Thanks for raising this important note. In the revised section 3, we added such information after comparing the global estimates from different methodologies (L382-388) as follows:
"It should be kept in mind that it is a purely academic exercise to show the effect of the different Tiers on total livestock methane emissions. As emphasized in the *2019 IPCC Refinement (IPCC, 2019)* Vol.4 Chapter 10 Section 10.3.1, "the Tier 2 method should be used if enteric fermentation is a key source category for the animal category that represents

a large portion of the country's total emissions", and "the Tier 1 method is likely to be suitable for most animal species in countries where enteric fermentation is not a key source category, or where enhanced characterization data are not available"."

L 178: "Assuming no changes in the distribution of livestock during the period 2000-2018, we estimated the gridded enteric". It seems unlikely that no change in livestock distribution would have happened between 2000 and 2018. Please explain the reference from which you deduced this assumption.
[Response] This assumption is due to data availability. To improve the clarity, we revised it (L208-213) as "We estimated the gridded enteric fermentation emissions by distributing country emissions into grid cells following the GLW3 livestock distribution data (Table S2). We assumed no changes in the distribution of livestock during the period 2000-2018 in the gridded products, as time-variable livestock distribution data, to our knowledge, is not available at global scale."

L 365: "Globally, we found that 88% to 91% of the livestock emissions come from enteric fermentation (Table S2)" the livestock CH4 emissions (please add "CH4")
[Response] We added it.

L 370: emissions between the four datasets (Figure S2), mainly due to the revised emission factors used in the 2019 Guidelines: please make clear which of the revised EF your are referring to (enteric? Tier 1a? Manure?)
[Response] We clarified it (L410-412) as "There are significant regional differences in livestock methane emissions between the four datasets (Figure S2), mainly due to the revised Tier 1 enteric fermentation emission factors used in the 2019 Guidelines and the Tier 2 method (the 2019 MT in Figure S2)."

L393: "On the other hand, emissions stayed almost constant in the developed regions between the two periods." I doubt that this statement can be made when applying a simple Tier 1 EF for estimating emissions from high productivity systems. Please make clear that this statement is valid when using Tier 1 methods only.
[Response] We revised the sentence (L435-438) as "On the other hand, estimated emissions decreased in the developed regions between the two periods when using the Tier 1 methods, while estimates using the 2019 MT method showed slightly increased emissions in North America and almost constant emissions in other developed regions as increasing yield and liveweight were accounted for."

L 411: "Ruminant meats are the most intensive livestock category" This statement is too coarse. Please specify more concretely in what sense you think that ruminants are most intensive (e.g. pigs and poultry are housed intensively, fed high intensity concentrates, are medically treated with high intensity,...) Also, CH4 emissions are only ONE parameter. Nitrogen emissions are also environmentally relevant.
[Response] We specified it (456-457) as "Ruminant meat have the highest methane emission intensity per kg of protein among major livestock productions."

L 416 "Milking cows" (not "Milk cows")

[Response] We corrected it.

L 459: "The attribution shows 459 that 30% of the changes are due to changes in the emission per kg protein of individual category": "Individual category": syntax is not correct
[Response] We revised it as “different livestock categories”.

L 487: "the decrease is mainly 486 (>63%) due to the changes in the emission per kg protein of individual category": "Individual category": syntax is not correct
[Response] We revised it as “different livestock categories”.

L 537: "Moving to the methodology of the 2019 IPCC Refinement (IPCC, 2019) is important, as the differences can be substantial, particularly in regions such as Sub-Saharan Africa, Near East and North Africa, and South Asia, where large positive trends on livestock production (Figure S12) and emissions (Figure S13) are projected in the future scenarios.": indeed, this was one of the main reasons for integrating the Tier 1a factors into the Refinement. It is difficult to understand why this seems to have been excluded from the authors´ estimations.
[Response] In the revised MS, we presented the estimates of enteric fermentation CH_4 emissions using the IPCC Tier1a method for a comparison. However, due to the limited regional information on the production systems from the IPCC guideline, we can only estimate enteric fermentation methane emissions using the Tier 1a method for dairy cows, meat and other non-dairy cattle and swine in Latin America, Africa, Middle East, Asia and India sub-continents. We found that global estimates using the 2019 T1a method (see section 2.2) are nearly the same as that using the 2019 T1 method (< 0.2% differences; Table S2) with differences ranging from 0.01% to 3.4% in regional estimates, thus we do not discuss the emissions using the 2019 T1a method in the rest of the MS (L379-382). Please see our response to your previous comments (L 144) for further detail.

L 558 "contributed by the efficiency change for dairy cow": dairy cows
[Response] We correct it across the MS.

L 562: "The potential is the largest in developing countries where the current efficiency is low (i.e., emission intensity per kg protein is high) and a large increase in livestock production is projected. For example, in our projections under the Business As Usual (BAU) scenario, 60-65% of the global reduction in livestock emissions by 2050 due to improving efficiency (compared to baselines where intensity is constant in the future) can be contributed by the top ten countries with the largest reduction potential. Most of them are developing countries in Asia, South America and Africa (Fig. 5 and Figure S15-16)." I think that this is a VERY relevant statement! It is fully in line with what we know about cattle nutrition and relationship between milk yield and ruminant CH4 emissions. The most prominent reduction of CH4 emissions / kg milk is observed between an increase of ca. 3 500 to 6 000 kg milk per cow and year. Milk yield in the high production systems is already around 10 000 kg or higher and here there is only little room for methane reduction through productivity increase. On the other hand, a production increase requires high shares of concentrates (= competition with human nutrition) and encounters potential health problems in cows. Milk yield increase at lower production levels can, however, be achieved

with better roughage quality and does not require concentrate input. Please work on this a little bit more in your paper, because it is a very relevant aspect.

[Response] Thanks for the suggestion. In the revised MS, we added the discussion on the low livestock CH_4 mitigation potential in the developed countries, and the potential risks (L622-633; see also below). The discussion on the high mitigation potential in developing countries was there in the previous version, and we largely revised it following your suggestions.

"Livestock productivity of milk and beef in most developed countries is already high nowadays (methane emission intensity is already low; Fig. 2), and there is only little room for methane reduction through productivity increase (Figure S10). On the other hand, further productivity increase requires high shares of concentrates (i.e., potential competition with human nutrition from plant-based food (Gill et al., 2010)) and encounters potential health problems in cows (see review by (Herzog et al., 2018)). In addition, the intensive livestock breeding and management have resulted in fragile systems that do not adequately handle their manure causing air and water pollution. There is a trend that some developing countries are moving from high efficiency systems towards more extensive livestock systems (such as "free range" chicken and grass-fed beef; e.g., (Cheung & McMahon, 2017)). Therefore, there is possibility that the emission intensity per kg protein in those developed countries will increase, which is opposite to our assumption of constant of decreasing emission intensity."

L 589 "The continuation of past decreases in emission intensity, especially in developing countries, can be achieved through the transition of livestock production systems from extensive rangeland systems to mixed crop-livestock and industrial livestock systems" I do not know what you mean by "industrial livestock systems" (this would need to be defined), but if you mean the high intensity, high input systems that we see in the industrialized countries, then I would strongly advise not to recommend a change towards such systems for developing countries. They should not repeat the mistakes made in the industrialized countries!

[Response] Thanks for the suggestion. We agree that industrialized high input systems are not environmentally sustainable. Thus, we deleted the "industrial livestock system" in the text to avoid misleading. Following your suggestions below, we also added the other important way for productivity improvement "through improving livestock management within the existing systems" (L644).

L 595 "In addition, new technologies such as feed supplements can also reduce methane emissions from rumen" feed supplements as mitigation technology for developing countries? This is unlikely to work. Even in the high intensity countries these additives are not commonly used on commercial farms.

[Response] We intended to give the potential strategies to reduce livestock CH_4 emission, but also emphasized the "adaptability issues and side-effects to be considered when implementing these strategies" latter this paragraph.

L 601: "A shift in the production system usually indicates an increase in the consumption of crop-based grain and/or high-quality fodder in the diet." No! This is not always the case. You can get up to 7 000 kg milk per cow and year without concentrates. Please stay on you

clear line of argumentation and show that a productivity increase based on better roughage quality and better grazing management will be more effective than a further productivity increase with even more concentrates.
L 603: "It should also be kept in mind, however, that moving from a low to a high production system may be infeasible in some semi-arid regions without imports of crop feed, as local rangeland is the dominant and climax vegetation and increasing crop plantations for feeding livestock is impossible due to water limitations" No! Improvement in production efficiency is NOT about moving from low to high production. It is about improvement of cattle management in line with the natural circumstances in the respective regions. There is still lots of room for improvement and no need to create high production systems.
[Response] We agree with the reviewer that the above two sentences can be misleading. We therefore revised the statement (L654-665) as "A shift in productivity might involve an increase in the consumption of grain-based feed and/or high-quality fodder in the diet, but it can also be effectively achieved through better roughage quality and better grazing management. For example, in semi-arid regions where increasing crop production for feeding livestock is impossible due to water limitations (e.g., central Asia), improving grazing management to increase productivity should be prioritized as a sustainable solution rather than moving from low to industrialized systems (i.e., landless livestock systems with livestock fed by grain-based feed and/or high-quality fodder). Improving livestock production efficiency should always be in line with the natural circumstances in the respective regions. The optimal strategy should consider also other relevant sustainability goals like biodiversity, water pollution through nutrient runoff, and potentially implications for livelihoods and resilience to climate change impacts.".

L 607 "In addition, feed-producing croplands compete with those producing plant-based food" No! Such a coarse and general statement is for sure not helpful when it comes to cattle and milk production management. Cattle can convert non edible crops to high value protein and there are large areas where arable production (i.e. crop production for human nutrition) is not possible.
L 609 "Importing high-quality feed like soybean has been a choice for many countries to increase feeding efficiency, but it may also induce large GHG emissions due to the expansion of cropland from deforestation" This may be true, but is not very much related to the topic of the paper (I suggest to delete). It is disappointing to see such a weak ending in such a very nicely written and helpful paper. The statement is coarse and not sufficiently differentiated to be helpful in this context. Please end the paper with conclusions of your most relevant findings related to the inventory methodology (what changes did the methods deliver and why and what conclusions do you draw for inventory preparation?) and to the regions where a production increase will be most helpful.
[Response] We agree that the above two sentences pointed out by the reviewer are not directly relevant to our results, and the point of view is incomplete which might be misleading. So we deleted them in the revised MS.